A theoretical framework for integrated STEM education

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Abstract

For several decades there has been a broad consensus on the need to promote scientific literacy and, ultimately, to promote the broad development of student competency from an early age. However, many of the results recorded in the educational field are not very encouraging. Although interdisciplinarity has a much broader trajectory, the continuous questioning of traditional teaching methods, due to their inefficiency, has given rise to the emergence of educational approaches that integrate the teaching of diverse scientific disciplines in a more contextualized, coherent, and comprehensive manner. The body of empirical research on the application of these approaches has grown, while leaving behind some essential theoretical questions. In the present work, a theoretical framework is proposed for integrated science, technology, engineering, and math (STEM) education, a current teaching approach with the greatest momentum. Based on the epistemological stance of Larry Laudan, three levels of scientific commitment are adopted: with theories, with methods, and with the aims. Regarding the theoretical commitment, three axes of support are established for this framework: epistemological, psychological, and didactical. This mechanism allows us to construct a consistent model that may contribute to developing coherent integrated STEM education. In addition, an example of a real application of this theoretical framework is provided in the design, implementation, and evaluation of a STEM didactic unit in the primary education stage, demonstrating its coherence and viability.

Keywords Theoretical framework, Philosophy of science, Humanist science education, Competency, Integrated STEM education, Interdisciplinarity

1 Introduction

In the last decades of research in the field of science education, two topics continue to appear in many international articles and research reports. First is the concern over the indispensable nature of scientific literacy for citizens to exercise their full rights (European Commission [EC] 2015; National Research Council [NRC] 1996; NGSS Lead States 2013). Second is the concern of many governments and organizations regarding the decrease in the number of young people choosing to study scientific-technological disciplines at the end of their compulsory schooling (Archer *et al*. 2010, 2012, 2013; DeWitt and Archer 2015; NRC 2008, 2012, 2014). Consistent with these topics, Kezar *et al*. (2017) have affirmed that "for the past 20 years, countless reports have been issued calling for reform of undergraduate education to improve student learning, persistence, and graduation rates for students in science, technology, engineering, and mathematics (STEM) majors" (p. 217). If undergraduate education has to be reformed, K-12 education has also to be transformed (NRC 2012).

In order to address these problems, several approaches have been incorporated and established in the field of science education. Without pretending to be exhaustive, some with a robust research trajectory can be named, such as problem-based learning (Gallagher *et al*. 1995), the use of History and Philosophy of Science (Matthews 2014, 2018), modelling (Gilbert and Justi 2016; Greca and Moreira 2000), argumentation (Erduran and Jiménez Aleixandre 2007), computer simulations (Smetana and Bell 2012) or inquiry teaching (Lazonder and Harmsen 2016). In addition, given the continuous criticism of traditional teaching as a simplistic reductionist approach addressing the disciplines in isolation (Connor *et al*. 2015), some approaches within the framework of disciplinary integration have emerged in the field of science education. There is evidence that integrated projects produce favorable effects on K-12 students' learning and attitudes (Gresnigt *et al*. 2014; Kang, 2019). An educational approach of special interest, under the acronym STEM (science, technology, engineering, and mathematics), has developed that advocates the literacy of people in the four disciplines (Bybee 2013). From a broad point of view, it has been considered that effective STEM education will capitalize on students' interests and early experiences, build new knowledge on what they already know, and provide experiences that involve them and awaken their interest in scientific practices (NRC 2011).

Given the educational projection of this approach, many empirical studies regarding its practical application have been accumulating over recent years, especially in the field of science education (Brown 2012; Mizell and Brown 2016). However, some essential theoretical questions that offer a better conceptual understanding of the scope and constraints of empirical investigations have not received the same attention. In that regard, some relevant contributions are worth mentioning: conceptual frameworks to design STEM lessons (Chu *et al*. 2019; Kelley and Knowles 2016), conceptual models for assessing their efficacy (Murphy *et al*. 2019; Quigley *et al*. 2017), and descriptive frameworks useful for identifying, describing and investigating specific integrated STEM initiatives (Falloon *et al*. 2020; NRC 2011, 2014). However, despite their significance, these studies have not delved into the psychological view or into coherence with epistemological foundations, thus limiting their application and raising some of the previously mentioned issues (McComas and Burgin 2020; Millar 2020; Zeidler 2016).

Duschl (1990) stated that adopting a curricular perspective that evolves from a complex set of scientific processes based on epistemological principles means that a broader range of curricular approaches can be integrated into the K-12 education stage. However, as has been commented, a complete theoretical foundation supporting integrated STEM education is still lacking in the literature, especially from an epistemological viewpoint (Authors; Reynante *et al*. 2020). Based on these arguments, we consider it especially relevant to adopt an epistemological stance that is consistent with integrated STEM education. As will be seen, the epistemological approach followed here demands express statements of coherently interrelated aims, theoretical assumptions, and methodological principles for integrated STEM education. Hence, the objective of this position paper is to propose a theoretical framework for integrated STEM education, steering it towards the development of the student competency and bringing this approach closer to a more formative and humanistic position, essential in scientific education (Zeidler 2016; Zeidler and Sadler 2007).

In what follows, some crucial issues on STEM education are collected and then the general structure of the theoretical framework is presented. Based on this structure, the particularities of the theoretical framework for integrated STEM education are further detailed. Once the framework is known in detail, an example of the theoretical framework applied at the primary education stage is shown. Finally, some of the educational implications of the STEM approach are presented.

2 Some crucial issues concerning STEM education

The literature contains variations on the meaning of a STEM education (Breiner *et al*. 2012; Ritz and Fan 2015). In fact, this issue has been pointed out in a recent review indicating that these multiple interpretations involve a wide spectrum of disciplinary integration models, ranging from teaching one of the STEM disciplines, to considering it as a discipline in its own right (Martín Páez *et al*. 2019). In this sense, although Gresnigt *et al*. (2014) indicated not long ago that there were very few “data-driven” research reports and inquiries into the theoretical foundations of integrated curricula, a lively debate on disciplinary integration and the nature of the STEM (NOSTEM) approach has recently been established within the scientific community (see, for example, issue 4 of volume 29 of this journal dedicated to this discussion). From our perspective, STEM education implies a higher level of integration than the treatment of the four separately defined literacy branches, which has been called integrated STEM education (Kelley and Knowles 2016) and that can be supported by the adoption of a particular epistemological view. In our recent work in the context of this discussion (Authors), we have established a framework for philosophical discussion on integrated STEM education, adopting a model of a "seamless web" of the relationship among science, technology, engineering and mathematics through the lens of Reconceptualized FRA-to-NOS (RFN) (Kaya and Erduran 2016) as an analytical tool to identify some central features of the NOSTEM. Regarding the disciplinary integration, as Coria and Porta Massuco (2020) state, it is a burden to try to “define” those concepts, given the fact that doing so implies making certain connections that tend to be complex while leaving aside, or making invisible, other ones. In the academic field, we can speak of multidisciplinary when several disciplines coexist to address aspects of the same problem where, although working as a team, each discipline works from its perspective. Regarding interdisciplinary, it can be considered in a broad sense —associated with multidisciplinary processes with potential interaction— or an interdisciplinary in a strong sense —linked to effective integration dynamics—. The first usually appears as a cooperative way of working to solve practical problems within various institutions critical to the daily life of societies —hospitals, schools, etc.— as well as in a whole range of informal situations, and tends to persist in the time. However, it should be pointed out that collaboration is an additional facilitating factor that reinforces interaction, but it is not part of the definition of interdisciplinarity per se (Frodeman *et al.* 2017). On the other hand, it should be clarified that interdisciplinary does not deny the knowledge of content and methodologies of those who participate in a project, but rather implies the generation of new codes, common understandings, methodological conceptual agreements and ways of formalizing exchanges. It is a qualitative leap that, when achieved, is irreducible to the participating disciplines. It is usually stated that transdisciplinary, besides promoting interrelations because of the convergence of specialists that think beyond their disciplines, also incorporates a several social actors. The concept of an extended peer community, created by Funtowicz and Ravetz (2000), is key when thinking about both interdisciplinary in the strong sense and transdisciplinary, given that it extends the legitimacy of those involved in the process of knowledge generation to the same communities that live the complex problematics, that are object of the transdisciplinary. For our model, we need to translate these concepts to the instructional point of view. For doing so, we adopt English’s (2016, p. 2) definitions: the multidisciplinary level occurs when concepts and skills are learned separately in each discipline but within a common theme; at the interdisciplinary level, closely linked concepts and skills are learned from two or more disciplines with the aim of deepening knowledge and skills; and the transdisciplinary level implies that knowledge and skills learned from two or more disciplines are applied to real-world problems and projects, thus helping to shape the learning experience. This conception of transdisciplinary is also presented in Frodeman *et al.* (2017), where an extensive discussion on interdisciplinarity can be found.

In addition, many definitions of STEM education and proposals for its implementation suggest positions close to professionalization and the coverage of economic needs (Breiner *et al*. 2012; Bybee 2013; Herschbach 2011; Zollman 2012). In this sense, several criticisms have been advanced, especially with regard to the sociopolitical silence that is apparent in a lot of STEM policy (Chesky and Wolfmeyer 2015; Gough 2015), that makes it "unlikely [that] students will engage in criticism of STEM processes and practices that support economic growth, and instead will orient students to support them" (Hoeg and Bencze 2017, p. 857). Among others, Zeidler (2016) considered that if STEM education is not reframed within broader sociocultural and political frameworks, then the educational model of STEM initiatives will be deficient. In addition, there is a clear under-representation of certain groups in the STEM landscape (Vallett *et al*. 2018).

We agree with these critical views, and so, in line with Zollman (2012), we believe that, in the educational field, integrated STEM education should aim at developing an integrated education and continuous learning, aiming for a higher level of competency development for all citizens from a humanist perspective (Aikenhead 2015). That is, in our understanding, integrated STEM education, instead of prioritizing employment after the completion of school, should engage students in more active and participatory community-grounded science, inclusive of calls for social justice and citizenship (Calabrese Barton 2012). We believe that scientific vocations will emerge naturally from this development of humanistic competency, a question that has previously been discussed elsewhere (Maltese and Tai 2010). Thus, given the complex and comprehensive nature of the competency construct and its multiple dimensions, the use of integrated STEM education appears to be an appropriate and beneficial approach for that purpose (Authors).

In all, integrated STEM education, is focused on complex problems (Pleasants 2020), preferring interdisciplinary and transdisciplinary approaches, which have an iterative process of creating new questions from different disciplines (Quigley and Herro 2016). In this position paper, integrated STEM education is understood as an educational approach that can develop competencies among students in an integrated and humanist manner (Aikenhead 2015).

Finally, it is relevant to highlight that in these integrated approaches, one of the subjects often has a dominant role, depending on the focus of the lesson or project (NRC 2014, p. 42). However, deviations appear in the literature regarding STEM models where the central emphasis is placed on two or more disciplines. Most of the proposals have focused on science and mathematics (Breiner *et al*. 2012; Bybee 2013; Hoachlander and Yanofsky 2011; Kelley and Knowles 2016; Sanders 2008; Wang *et al*. 2011), while the integration of technology and engineering, is less well developed (Bybee 2010; Herschbach 2011; Hoachlander and Yanofsky 2011; Kelley and Knowles 2016; Williams 2011), given that those subjects are not usually present in the early stages of compulsory education (NRC 2011). Nevertheless, "the infusion of 'engineering practices' in the Next Generation Science Standards in the USA signals a major shift in curriculum policy for integrating related domains to science teaching and learning" (Erduran 2020, p. 781). Thus, in many integrated STEM and STEAM (STEM+arts) education programs, design practices in technology, engineering and the arts are increasingly emphasized (Kang 2019), as design problems are all real-world problems, providing rich contexts in which learning and the application of science and mathematics concepts and practices can potentially happen when students are actively looking for solutions (Kelley and Knowles 2016). It is precisely the complexity of integrated STEM education that makes it more powerful, as the integration process is not a linear/deterministic process.

3 Structure of the theoretical framework

The present construction of the theoretical framework for integrated STEM education is based on the epistemological position of the American philosopher of science, Larry Laudan. Although Laudan assumes that no single theory of scientific change exists, he proposes, from his pragmatic and rational view, a series of criteria that operationalize the construction of a normatively viable philosophy of science. Within the metamethodology created by Laudan (1977), scientific progress is determined by the number of problems a theory can solve. It is defined around the effectiveness of a theory in terms of solving problems. From this perspective, science represents a permanent activity of problem solving, and the rule guiding scientific progress is the coexistence of different research traditions. The comparison between theories leads to a rational and progressive change in which there is no cumulative conservation. Theoretical gains and losses coexist based on the effectiveness of scientific problem solving. Thus, problems represent the central point of scientific thought, constituting scientific inquiries, the challenging questions that generate the need for resolution in the scientific community. Laudan distinguishes between two types of scientific problems: empirical —any aspect of the natural world that surprises us as strange or that requires an explanation; that is, substantive questions about the facts constituting the domain of any science— and conceptual —deficiencies or internal inconsistencies of the theories, that is, problems, conflicts, or controversial aspects presented within a theory or a theoretical framework—.

From Laudan's philosophy of science, a theory —or a scientific response— solves an empirical or a first-order problem when it —together with constraints— explains, clarifies, and answers the problem. A theory solves or eliminates a conceptual or higher order problem when it overcomes the conceptual difficulties or theoretical conflicts of its predecessor theories or when it presents no conceptual difficulties. Thus, a theory is more progressive when it explains more empirical relationships and obviates more conceptual problems. Based on Duschl (1990), progressive theories are those most closely approaching or entering the core of the research programs of Lakatos (1970).

Laudan proposed his Reticular Problem Solving Model in an attempt to address rational and regulated scientific progress. The reticular model acquired its name because of his opposition to the hierarchical model commonly used and accepted by the philosophers of science, such as Kuhn (1962), in the first half of the twentieth century. This hierarchical model assumes that factual/theoretical disputes are resolved by appealing to methodological principles and methodological disputes are solved when related to the objectives that science establishes. That is, hierarchical models emphasize theory-related commitments over and above the other two. In Laudan's view, theoretical assumptions, methodological principles and research aims are interrelated, and scientific change is more gradual and less holistic than the one proposed by Kuhn, in which an older paradigm —with its theories, methods and aims— is replaced in whole or in part by an incompatible new one.

Within this framework, Laudan (1984) presents the Triadic Network of justification. This model postulates an epistemological analysis of scientific development composed of three levels of scientific commitment with the same status that interact in complex ways, the modifications of which are not always simultaneous[1]: commitment with theories, with methods, and with the aims. There is a strong interrelation between these three levels of scientific commitment:

- The methods justify the theories.
- Theories limit the methods, restricting the methodologies to be used.
- The aims, objectives, or goals justify the methods; they indicate the choice of methodologies to be used.
- The methods clarify the feasibility of the aims, objectives, or goals; they demonstrate their viability.
- Theories must be harmonized with the aims, objectives, and goals.

These three levels of commitment are postulated by Laudan for any contribution to the construction of scientific knowledge and as participants within a complex process of adjustment and mutual justification. As a result, a decision with respect to one element can be motivated from a position with respect to another element. According to Laudan (1984), the elements of this model imply "that our factual beliefs drastically shape our views about which sorts of methods are viable, and about which sorts of methods do in fact promote which sorts of aims" (p. 62). Decisions on scientific aims, methods and theories become an exercise in empirical comparison, rather than a matter of adherence to conventions. We adopt these levels within the present theoretical framework (Figure 1) for the composition of a cohesive and coherent model that supports integrated STEM education.

Fig. 1 General scheme of the Triadic Network. From Laudan (1984)

We consider that this model is acceptable, so that integrated STEM education can be presented with greater clarity, because it demands express statements of aims, theoretical assumptions, and methodological approaches —in fact, that last point is the main aspect addressed in much of the STEM research literature—, which must be coherently interrelated, prompting a healthy discussion focused on all the elements involved in both teaching and learning. It should be noted that this structure means that the model can be evaluated and, therefore, modified if so required, which contributes to its effectiveness.

In the next section, we present our own selection of methods, theories and aims for integrated STEM education.

4 The triadic network for integrated STEM education

As previously indicated and based on the epistemological framework assumed about the NOSTEM (Authors), integrated STEM education in this paper is understood as a possible channel for integrated competency development. Therefore, within the triadic network for integrated STEM education, the goal consists of improving the competency development of the students, specifying an appropriate methodology that makes this goal possible. In this regard, it should be noted that we define competency (Authors) as a multidimensional construct that encompasses seven dimensions: knowledge, know-how, attitudes, context, communicative solvency, awareness and nature of disciplinary knowledge. If, as has been pointed out, the traditional methodology is not effective for improving competency, a different approach must be followed. Consistent with the view that science represents a permanent problem-solving activity and with the adopted definition of STEM, inquiry is proposed as the main didactic methodology, largely in line with the interest in competency development (Aguilera Morales *et al*. 2018). Inquiry, inquiry-based science education (IBSE) and inquiry-based

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[1] Some examples based on historical scientific events can be found in chapter four of Laudan's book, *Dissecting the holistic picture of scientific change* (1984).

learning (IBL) have been defined both as ways to teach and to learn science, implying that students observe; raise questions; seek information; plan research; review existing knowledge in the light of experimental evidence; use tools to collect, analyze and interpret data; propose answers, explanations, and predictions; and communicate results (NRC 1996, 2000). Of special interest for the aims that are addressed is the use of socio-scientific inquiry-based learning (SSIBL), where the integration of citizenship education, socio-scientific issues (Crippen and Archambault 2012), and IBSE provides a model for both using and building scientific knowledge, to enable change by asking authentic questions; conducting inquiry-based learning and taking action (Levinson 2018).

Although there are many recommendations about the use of inquiry and manifestations in terms of its general effectiveness in teaching science (Bevins and Price 2016; EC 2007; NGSS Lead States 2013), in this framework, guided inquiry —in any of its versions— is used, (Bevins and Price 2016; NRC 2000) because it is the model that seems to provide the best learning results (Furtak *et al*. 2012; Lazonder and Harmsen 2016; Minner *et al*. 2010; Romero-Ariza 2017). This adoption does not nullify the possibility of combining inquiry with other methodologies or using others, provided they can make the desired goal viable, such as Project Based Learning (PBL) (Capraro *et al*. 2013), engineering design process (NRC 2009) or modeling and argumentation (Develaki 2020). In this way, the repeated insistence on the use of certain methodologies for the integrated STEM approach (EC 2015; NRC 2011, 2014) is justified by the aim that is pursued.

Finally, the theoretical level is incorporated into the network, whose constructs have been based on three compatible axes: epistemological, psychological, and didactical. The articulation and interrelation of these three axes, previously considered for the production of knowledge in the field of science teaching (Artigue 1988; Authors; Buty *et al*. 2004), completes a coherent and consistent model that fits our main objective. As described below, the choice of theoretical constructs for each axis was determined both on the basis of their internal consistency and their consistency with the other two levels of the triadic network. Just as no one methodology can guarantee the viability of integrated STEM education, neither is any one set of theories consistent with the methodology that is used. Following the epistemological axis, essential for the understanding of the principles, foundations, and scientific methods, Laudan's position has been adopted. The theory of conceptual fields of the French psychologist, Gérard Vergnaud, constitutes the psychological axis that offers a means of interpreting the way in which the students conceptualize. Although the previous theoretical constructs have important didactic consequences, a specific didactical axis must be adopted to support the teaching process, considering the didactic transposition. In proposing the didactical axis, the position of the French didactic researcher Jean-Louis Martinand has been considered, specifically his *objective-obstacle* notion. This set of theories, which will be described below, restricts the adoptable methodologies, as will be seen in the next subsections.

Once the theoretical level established for the triadic network of integrated STEM education is described, it should be made explicit that, just as the theory of the epistemological axis has been justified by the adopted methodology, the constructs of the psychological and didactical axes, in addition to being compatible and consistent with the epistemological axis, must be harmonized with the aim; this effort is required since the objective-obstacle notion appears necessary to explain competency development (Perrenoud 1997, 1999), and the theory of conceptual fields allows some aspects to be qualified, such as the long-term stability of the competency (Perrenoud 1997).

In summary, the triadic network for integrated STEM education is composed of a discourse coming from French didactics —with Vergnaud and Martinand at the theoretical level and Perrenoud at the aims level— in turn coherent with Laudan's epistemological view —also at the theoretical level— and with the choice of active, problem-based, experimental, student-centered and collaborative didactical methodologies —at the methodological level—. It should be noted that this decision made by the researchers is in turn validated by the empirical results obtained from its implementation using design-based research (Author; Authors; Authors; Authors).

Figure 2 shows the triadic functioning model created for integrated STEM education, indicating the location of the three axes that are presented, with a detailed explanation. Note the importance of the complex process of adjustment and mutual justification of the three levels of commitment.

Fig. 2 Model of triadic functioning for the theoretical framework of integrated STEM education

Through this framework, a more holistic perspective of integrated STEM education is provided, since it establishes a reasonable balance between the two main research approaches traditionally adopted in science education: the orientation towards science and the orientation towards students (Duit 2006). This perspective has already been shared by several researchers in the area (Dahncke *et al*. 2001; Duit 2006; Duit *et al*. 2005; Fensham 2001; Méheut and Psillos 2004; Psillos 2001).

4.1. Epistemological axis

In addition to the fact that Laudan's problem-solving model (1984) provides a way of combining the different levels of scientific commitment as discussed above, another intrinsic aspect of his philosophy is at the theoretical level. His notion of scientific progress and his conception of the problem constitute a fundamental construct for integrated STEM education. The relationship is obvious between Laudan's notion (1977) of scientific progress, the resolution of a larger number of problems, and the conception that is adopted here about the teaching-learning process from the approach of integrated STEM education, the nature of which is also based on the resolution of problems —emphasizing the resolution process—. In particular, Laudan considered empirical problems as science-related problems present in the daily life that require an explanation. Thus, within this theoretical framework, a problem is understood as a variety of situations, issues, tasks, designs, creations, assemblies, projects, activities, challenges, *etc.*, that are real and relevant for students and that demand explanations and/or solutions developed from the integration of STEM disciplines. Although there are epistemological differences in the kind of the problems solved in Science, Engineering, Mathematics and Technology, Laudan (1977) recognized that there are commonalities between scientific problems and problems defined in other disciplines, a view with which other authors who have reflected on this issue more recently agree. For example, in the words of Pleasants (2020): "each STEM field addresses problems that are substantively different from one another. Yet many interactions exist between the fields, because problems in one field often relate to and raise problems in another" (p. 837). So, aligned with our view of the NOSTEM (Authors), we consider that it is possible to generalize Laudan's epistemology of problem solving for all the STEM areas. Situations that are both real and relevant will help to achieve the proposed aims, so that students can acquire the tools to live in society and to contribute to it; in particular, situations that relate to contemporary global issues. As discussed in Duschl (1990), although it cannot be treated as a complete model in itself, this epistemological approach can guide both the selection and the sequence of scientific concepts to be addressed in the classroom; it can guide both the teaching and the learning of science.

Because the previous section touches upon this concept, the explanation of this epistemological theory will not be expanded upon. However, its emphasis is necessary from this perspective, the student's progress in the acquisition of competencies in all their dimensional complexity (Authors) can be inferred from the number of real problems that the student is capable of solving, the very essence of competency development. This perspective moves away from a purely technical resolution of the problems posed that only focuses on quickly fulfilling utilitarian objectives —as usually proposed in the more economistic perspective of the literature (Chesky and Wolfmeyer 2015)—, paying more attention to the learning process and its potential for integral competence development. Therefore, it adheres to a humanistic position where competence development is conceived as the integral development of the person (Delors 1996; United Nations Educational, Scientific and Cultural Organization [UNESCO] 2016) and not as a product created by economic needs.

4.2. Psychological axis

Vergnaud's theory of conceptual fields is framed within cognitive psychology and designates cognition as a basic ingredient for conceptualization (Vergnaud 1990, 1998, 2013). For Vergnaud (1990), all knowledge — how to do and how to express what is done— is divided into conceptual fields whose domains can take a long time to be apprehended. From this perspective, Vergnaud (1982) defined the conceptual field as a large informal and heterogeneous set of problems, situations, concepts, relationships, structures, contents, and operations of thought connected and probably interwoven during the acquisition process. In this theory, a concept is composed of Situations, Operational invariants and Representations (S, I, R).

An individual must face a large number and variety of situations (S) demanding their performance to achieve conceptualization or the domain of a conceptual field. In this way, situations constitute the concept's reference. The individual handles a whole set of mainly implicit ideas to deal with such situations, which Vergnaud calls operational invariants. Operational invariants (I) are composed of concepts in action —relevant or irrelevant primary ideas on which learning is built, in the sense of Ausubel's famous *subsuming concept* (Ausubel 1968), and theorems in action— true or false proposals about such concepts. A dialectical relationship exists between the concepts and the theorems in action; the concepts are ingredients of the theorems, and these are the properties giving the concepts their contents (Authors). Therefore, operational invariants are formed largely through experience and offer incontestable contributions to the development of an individual (Vergnaud 2007), constituting the meaning of the concept. Finally, operational invariants occur within the schemas, more stable cognitive structures belonging to long-term memory. Specifically, a scheme is the invariant organization of an individual's behavior in various situations, so, as the schemes are used and verified in situations, there is a balancing effect of cognitive structures through Piagetian *assimilation*, *adaptation*, and *accommodation* (Piaget 1936). With the exception of its generic concept of adaptation to the environment, the scheme specifically adapts to the situation (Vergnaud 1996).

Thus, for conceptualization to occur, teaching must manage students' operational invariants in a variety of situations that, in the case of approaching problems from integrated STEM education via the adopted methodology, arise naturally (Kelley and Knowles 2016). Although the operational invariants generally assume implicit knowledge, a small fraction usually manifests itself explicitly. At that point in time, the teacher must infer the distance at which the operational invariants handled by the students are from the real and expected scientific knowledge in education. Thus, the teacher is responsible for stimulating, creating, or inducing situations through social interaction (Vygotsky 1962), triggering a cognitive destabilization of students, remembering that such situations must be in their Zone of Proximal Development (Vygotsky 1978), which has been considered as the most difficult task for the teacher (Vergnaud 1998). However, in the case of integrated STEM education made viable through inquiry-based methodologies, the intrinsic group work, the multiple experimental situations, and the natural emergence of genuine problems are beneficial for enhancing social interaction and situations of cognitive imbalance.

Before continuing, it is necessary to indicate that what Vergnaud takes from Vygotsky with respect to social interaction, although relevant, could be extended and/or modified with respect to some cultural, linguistic or attitudinal aspects —for example, local culture, language or beliefs— that could be relevant and that in successive tests of this model in different cultural contexts could be necessary when choosing the problems to be addressed and designing the sequences in a contextualized manner. In this sense, the choice of a psycho-social framework for conceptualization can be a "variable in the framework" and could be replaced or integrated later on.

Also necessary are the representations (R) or symbolism that the individual adopts in the process of conceptualization. These are explicit and symbolic manifestations and compose the meaning of the concept. Students' representations, therefore, constitute an important source of benefit to the teacher wishing to understand the way students operate. However, frequently, and particularly in science and mathematics, students have different representations for the same concept —definitions, formulas, algebraic representations, graphs, drawings, *etc*.— and to master a conceptual field the subject must be able to use these different representations in a coordinated manner. In the case of inquiry-based methodologies or other related methods such as PBL or engineering design, the fact that students have to draw, design, discuss, plan, materialize, collect data, express themselves, make presentations, build, *etc*., assiduously implies the use of different representations that favor acquisition of the conceptual field.

Figure 3 shows the workings of the ideas presented in this theoretical construct when explaining the conceptualization process of students.

Fig. 3 Outline of the student conceptualization model and its influential theories

The level of conceptualization reached by the students, which includes the progressive mastery of the true concepts —with their operational invariants, domain of representations, and application to situations— will be equivalent to the level of competency development acquired. Obviously, students need schemes to master a situation that require a different competency domain. This need is adequately addressed in its complexity from the proposal of an integrated STEM education via the adopted methodology, given that around the same conceptual field a very large number of situations can be generated, gradually allowing students to achieve mastery in the field.

4.3. Didactical axis

Martinand's theory of the objective-obstacle has been adopted as a didactic support. Martinand (1986) proposed the existence of a dialectical relationship between the objectives of teaching and the obstacles standing in the way of achieving these, which is how the objective-obstacle concept emerges. In this way, the objectives of Martinand's theory correspond to the objectives posed in an integrated STEM didactic unit. The obstacles represent the alternative notions students have about the contents addressed in that unit. Thus, obstacles may be of various kinds, related both to all the dimensions of competency —*i.e*., conceptual, procedural, attitudinal, contextual, communicative and epistemological obstacles— and to the different types of competencies demanded by the problem that is addressed.

If the time available for the application of an ordinary didactic unit in the classroom is reduced, we consider that the objective a teacher must consider within the framework of integrated STEM education is not to overcome the obstacles, but to try to undermine or crack the representations —in the sense proposed by Astolfi (1994)— that students have, which we call *objective-representation*. These representations are identified when students make explicit their operational invariants and their Vergnaud's representations. To create the objective-representation, the teacher should consider at least the minimum necessary representations (Martinand 1988), which will be the appropriate path for further overcoming larger obstacles and, often, of strong resistance. This approach is consistent with the notion that complete control of representations is an illusion (Martinand 1988).

Given that the true objectives of scientific education need not be defined *a priori* and independently of the student's representations (Astolfi *et al*. 1997), the objectives of an integrated STEM didactic unit must be focused, to confront and to undermine the representations related to existing obstacles. These should not be skirted around, because they should be considered as something that is stimulating and dynamic, rather than as a negative aspect in learning (Astolfi 1999; Astolfi *et al*. 1997; Bachelard 1938; Martinand 1986). In short, this theoretical framework pursues the creation of an integrated STEM education whose objectives start from students' representations or obstacles to improve their competency development.

This didactic approach is consistent with both the epistemological axis and the proposed psychological axis, assuming a possible way of undermining or cracking representations and overcoming more long-term obstacles underlying scientific problems (Laudan 1977) that will be resolved within the domain of the conceptual field (Vergnaud 1990) addressed in teaching.

In what follows, an example of a real application of this theoretical framework is provided for the design of a didactic sequence for primary school.

5 Example of the theoretical framework applied at the primary education stage

The proposed model was applied in the design, implementation, and evaluation of an integrated STEM didactic unit of 19 sessions for the sixth year of primary education addressing the content of natural sciences and mathematics. These subjects are present in the Spanish curriculum and were taught in an integrated manner using guided inquiry and the engineering design process as main methodologies. Starting from Laudan's epistemological view of problem solving, a main problem was posed: *How can I design a lighting prototype for my study room?* It may seem like a simple problem; nevertheless, it prompts the discussion of sustainability and production-related issues, such as the demand for electricity, which are closely connected with the interests of students.

Thus, contents related to electricity, such as static electricity, source types, series and parallel circuits, insulating materials and conductors, energy transformations, and light and color —science—, were covered. Information and communication technologies were used, and technological aspects related to electric energy, lighting and its advances —technology— were discussed. Work was done on the design of a lighting prototype for a specific room —engineering—, and information needed to decide upon which lamps to use —considering cost, energy efficiency, and lifetime, among others — were managed as variables, tables, and graphs — mathematics—. It is worth stressing that the unit revolved around the solution of the initial problem and that its contents were addressed in an interdisciplinary manner as the students needed them to achieve a solution.

This didactic unit was designed to improve the development of the seven key competencies proposed in the Spanish Educational System regarding the curriculum content related to the problem: linguistic communication, mathematical competency, basic competencies in science and technology, digital competency, learning to learn, social and civic competencies, sense of initiative and enterprising spirit, and conscience and cultural expressions.

Regarding the psychological and didactic level, the process of design, implementation, and evaluation began by discovering the representations, from Martinand's point of view, that students had in terms of the content addressed in the unit, for example, on electricity, the management of mathematical data, or color. This process was carried out by consulting the information present in the specialized literature. It can also be done through a test application; the development of conceptual maps, diagrams, stories, reports, or drawings; and a long list of methods that give rise to the explanation and detection of representations or alternative ideas of students for further diagnosis. Then, some representations were selected that did not correspond to the scientific consensus and that were doable within the limited period of time in which the didactic unit was developed. Some of the representations selected were, for example, the belief that a battery is the only source of charge injected into wires like water in a pipe, that all types of graphs can represent any type of data, or that color is an intrinsic property of matter. In line with Astolfi (1999), the criterion for selecting the representations to be addressed was determined by the value that its splitting implied for competency development. With the selected representations, objectives-representations were generated that guided the design of the situations —from Vergnaud's perspective— aimed at undermining these representations. Taking, for example, the widespread representation that color is an intrinsic property of matter, the objective-representation of knowing the factors influencing the visual perception of the color of an object was generated, which led the students to inquire about observing a folio illuminated with different colored lights. From the integrated STEM approach made viable through the adopted methodologies, each problem offers a great variety of situations for students, for example, for each hypothesis worked through or each prototype designed and developed. Thus, each inquiry or design proposed involves a myriad of Vergnaud-type situations from the student's point of view. The *undermining* or *cracking* occurs when the *cognitive destabilization* manifests itself, which has already been alluded to in the psychological axis. This phenomenon creates an approach to the objective that will ultimately —and through the development of more didactic units throughout the course and the educational stage— signal the way forward, so as to overcome Martinand's objective-obstacle in the long term.

The entire process was operationalized by dividing the proposed main problem of designing a lighting prototype for a specific room into four specific problems: *What will our installation work with*? *How do we build our electrical installation*? *What kind of bulb do we use in our circuit?* and *What kind of light-emitting diode (LED) bulb should we use*? Each problem was addressed through the characteristic phases of guided inquiry.

To elucidate the didactic process used in the design of the didactic unit, Figure 4 shows an example of the transformation experienced by one of its objectives from its traditional conception to its elaboration from the present theoretical framework.

Fig. 4 Transformation of a traditional objective into other objectives based on the present theoretical framework

In the first case, the traditional construction of an objective, the objective of learning is constructed directly from the curriculum content, without considering the students' representations. The learning objective is created from a "blank" mental scheme. In addition, when students' representations with respect to the contents to be addressed are not known, the teaching process is focused on going around the obstacle, a situation that does not foster scientific learning. In the second case, construction of objectives from the present theoretical framework, although the learning objectives are logically related to the curriculum content, they are associated with the students' representations. Thus, within the integrated STEM education, the learning objectives are constructed when considering the representations underlying their mental schemes, as well as being focused upon or directed at the problems that is posed. In this case, unlike the previous case, the teaching process is focused on tackling the obstacle, allowing the overcoming of everyday life obstacles (Bachelard 1938).

Finally, the level of the students' competency development was deduced through the evaluation of the learning standards corresponding to the contents addressed, in which the representations used by the students and the explicit part of Vergnaud's operational invariants expressed by students were evaluated. This level of competency provided relevant information to check and to evaluate the extent to which the operational invariants were modified in the process of conceptualization and the implication on student representation, from Martinand's perspective. The analysis of the data collected after different implementations of the unit to a sample of $N = 121$ students reported high levels of competency development —more detail in Authors—.

Figure 5 shows the triadic operating model corresponding to the described example.

Fig. 5 Model of triadic functioning corresponding to an example of application of the theoretical framework in the design, implementation, and evaluation of a STEM didactic unit in the stage of primary education

6 Implications and conclusions

As well as we know the impossibility of conceiving the study of educational phenomenon from a single theoretical perspective, the same occurs in knowledge learning. Real problems transcend a unidisciplinary or single theory; the resolution of real problems is not the property of a single discipline. In contrast, it requires a wide range of contributions that transcend the content of a single discipline. Moreover, the eclecticism of the interdisciplinary often reveals new properties that would not be noticed in an isolated consideration. Grasping the complexity of reality and the development of a complex thought process, at some distance from the *blind intelligence* produced by uni-dimensional and disciplinary simplification (Morin 1990), is key to integrated STEM education, an educational approach that integrates branches of literacy that have traditionally been separately defined.

In this paper, a theoretical framework has been proposed for these two current multi-referential approaches of great scope, to improve the development of student competencies from a humanistic perspective; a framework that has largely been absent until now. The mechanism of the three levels of scientific commitment of Laudan has served to construct a theoretical framework to these approaches, founded on and consistent with both the depth and the essence of education.

From Laudan's perspective, this framework addresses a scientific problem: building a theoretical support for integrated STEM education that contributes to bringing it closer to a more formative and humanistic position and placing it in the educational setting with greater rigor and a commitment to the theoretical foundations of science education. The conceptual aspect of the problem represents the proposal of the theoretical framework itself. The empirical aspect implies an evaluation of whether the integrated STEM education contributes to improving competency development among the students, that is, the verification of whether this approach is better adapted for competency development than those that have traditionally been used. The study of student achievements with these approaches is the most developed aspect in the literature (Brown 2012; Mizell and Brown 2016), in addition to their creativity and problem-solving skills, attitudes, and interests towards STEM subjects. The results can nevertheless be questionable, since neither the aims nor the theoretical assumptions are always clearly stated.

Given the underlying theoretical complexity, some essential principles for integrated STEM education can be derived. We frame these principles in the three compatible support axes from the theoretical commitment, although given the theoretical interrelation, these principles should not be taken as intrinsic to the axes. Thus, from the epistemological axis we emphasize the importance of conceiving the teaching-learning process as a continuous problem-solving exercise —familiar to students—, which is the essence of integrated STEM education and scientific progress. On the road towards that solution, we must not forget, as highlighted by Duschl (1990), the commitment with theories, with methods, and with the aims. This methodological structure will be useful for science teachers, because it can provide a set of guidelines to help them plan and develop their science classes and didactic units (Duschl 1990). The psychological axis emphasized the need for the generation of a great quantity and diversity of situations. In this way, students will have the opportunity to manage a set of operational invariants, to develop, and to verify schemes and to achieve the conceptualization or mastery of the conceptual field related to the issues addressed in teaching. Finally, regarding the didactical axis, we emphasize, in line with Astolfi (1999), the didactic usefulness of the objective-obstacle concept for integrated STEM education, both as a way of selecting the objectives of an educational sequence —around overcoming one or more representations— as well as to regulate didactic interventions —the concept serves as a tool to understand what students say and do—. It is also important to emphasize the importance of considering representations and obstacles as a form of knowledge, which traditionally does not happen (Astolfi 1988).

Following Laudan (1977), this framework avoids two crucial and habitual conceptual difficulties: the justification of the use of certain methodologies congruent with the explanation of the process of students' conceptualization and the justification of the objectives or aims that are pursued. In addition, the framework allows for the formulation of new questions that transcend most operational characteristics present in the literature about integrated STEM education, such as the following:

- Is any problem adequate to achieve the proposed purpose?
- What level and kind of competency does the student reach?
- What schemes related to the practice of science and technology are developed by students using these methodologies?
- What are the objectives-obstacles that have been and should be overcome?
- Which methods are more efficient —understood in terms of the domain of the conceptual field and of overcoming objectives-obstacles— in reaching the proposed goal?

Knowing that the elimination of conceptual difficulties involves both scientific progress and the increase of empirical support (Laudan 1977), this theoretical framework is proposed with the intention of helping to offset a scientific advance, so far largely led by empirical studies. In addition, this framework guides the design of didactic proposals that allow the evaluation and modification of the assumptions —epistemological, didactical psychological and methodological— that support it. Speculation, reflection, and philosophical thinking have been used for critical clarification of an educational issue, a position that can allow the establishment of more humanizing educational reasoning. Likewise, the incorporation of this theoretical framework into the scientific knowledge of integrated STEM education can, through the holistic view provided by theoretical knowledge, lead to the assessment of empirical works and the gauging of their scope and limits (Gil Cantero and Reyero 2014).

In this position paper, we have adopted a particular set of theories, which might limit this theoretical investigation. On the one hand, therefore, some specific theoretical aspects that are implicit to this paper might be enlarged —for example, relating to the sociocultural perspective and epistemic knowledge—, and, on the other hand, other theoretical constructs —even other aims— could be adopted unlike the ones proposed here, as long as they comply with the triadic coherence also proposed in this paper.

So, leaving the doors open to continuous theoretical improvement and scientific advancement, this theoretical framework could be useful for moving towards the humanistic educational contextualization of integrated STEM education, which is already in full swing and in many cases is followed within the educational field without sufficient reflection and theoretical foundation, both of which are necessary. From a humanist perspective, this framework moves away from the more technical versions of STEM education that have previously been criticized (Chesky and Wolfmeyer 2015; Zollman 2012).

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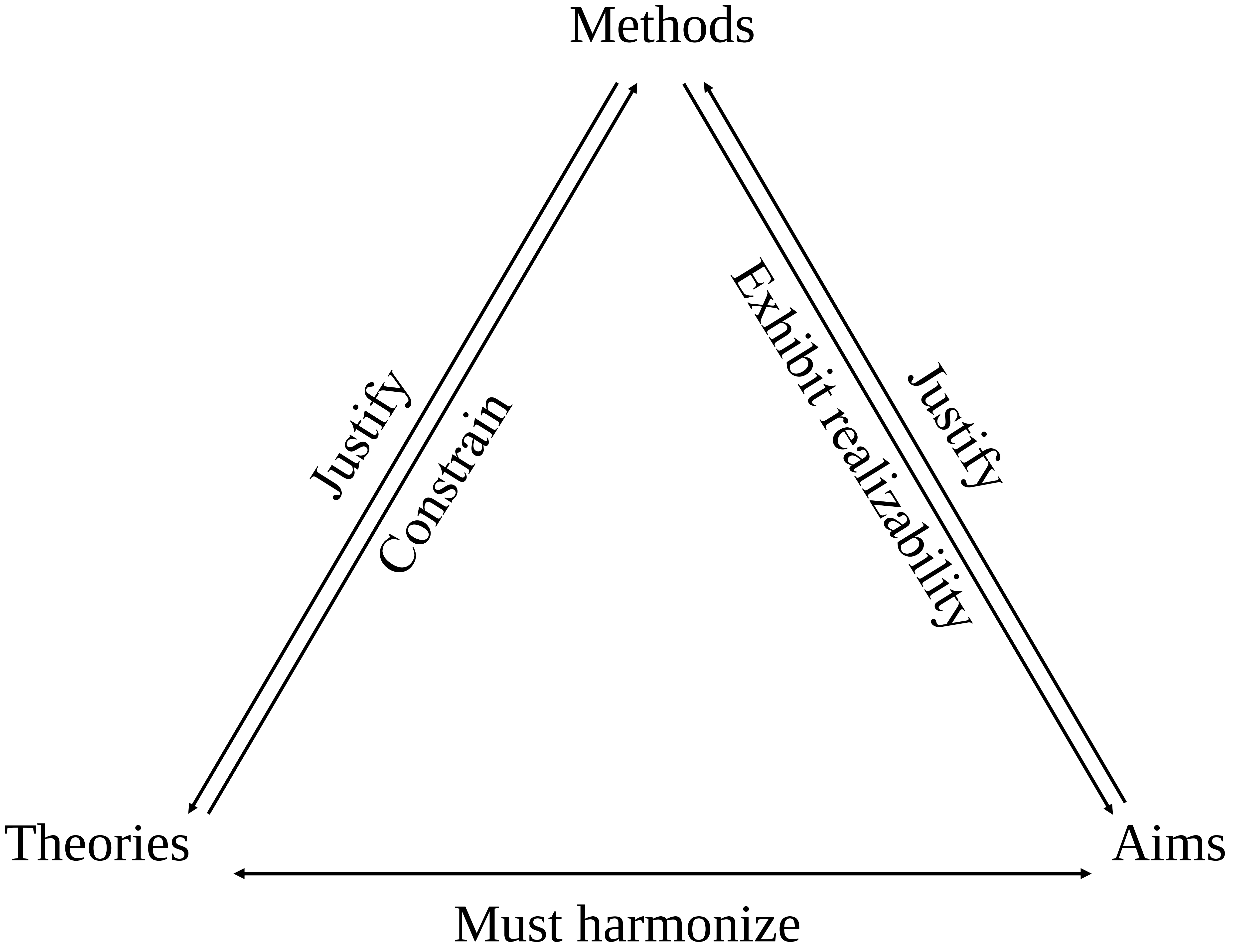
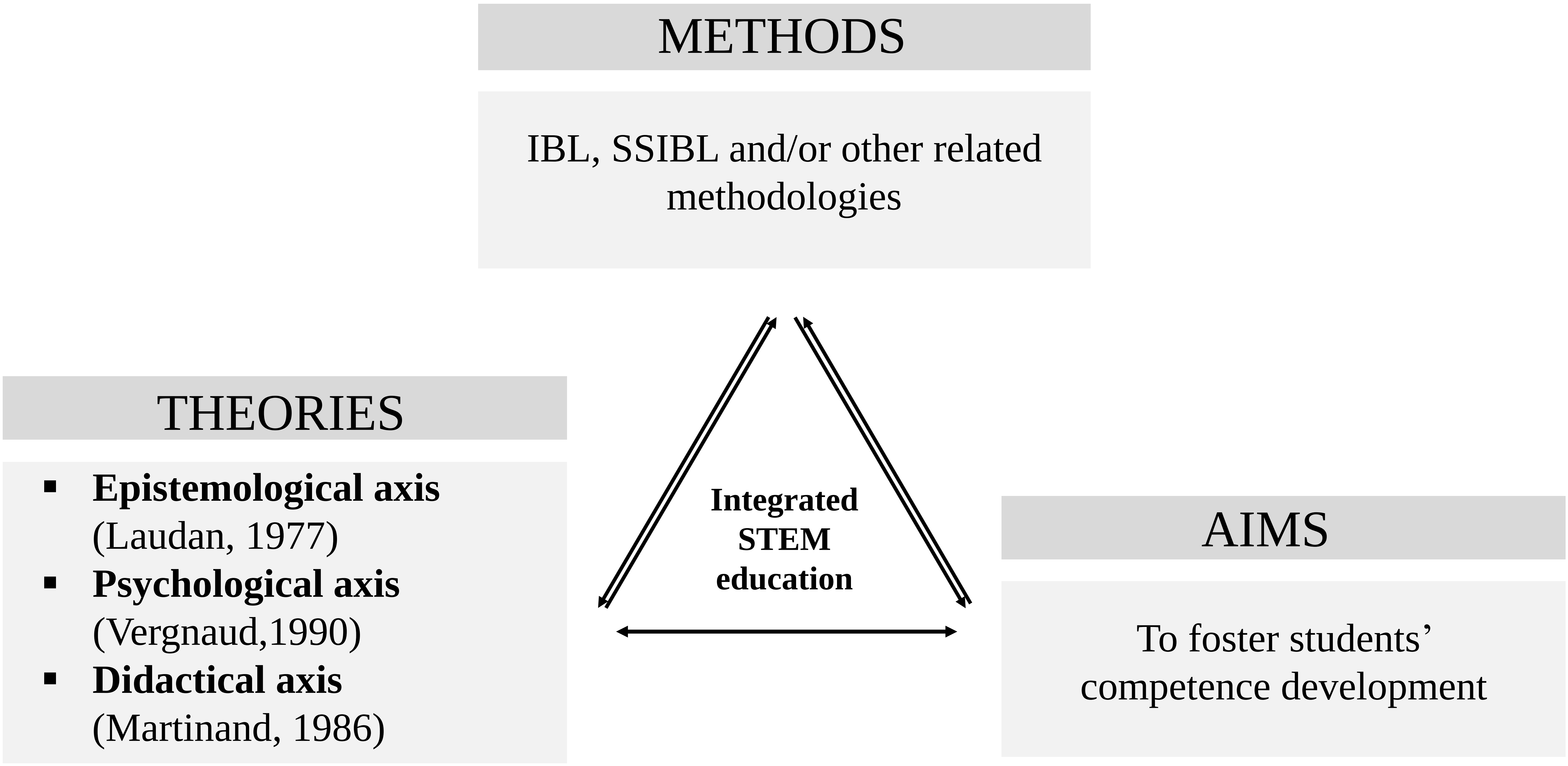

Methods
Justify
Constrain
Exhibit realizability
Justify
Theories
Aims
Must harmonize

Figure 2



METHODS

IBL, SSIBL and/or other related methodologies

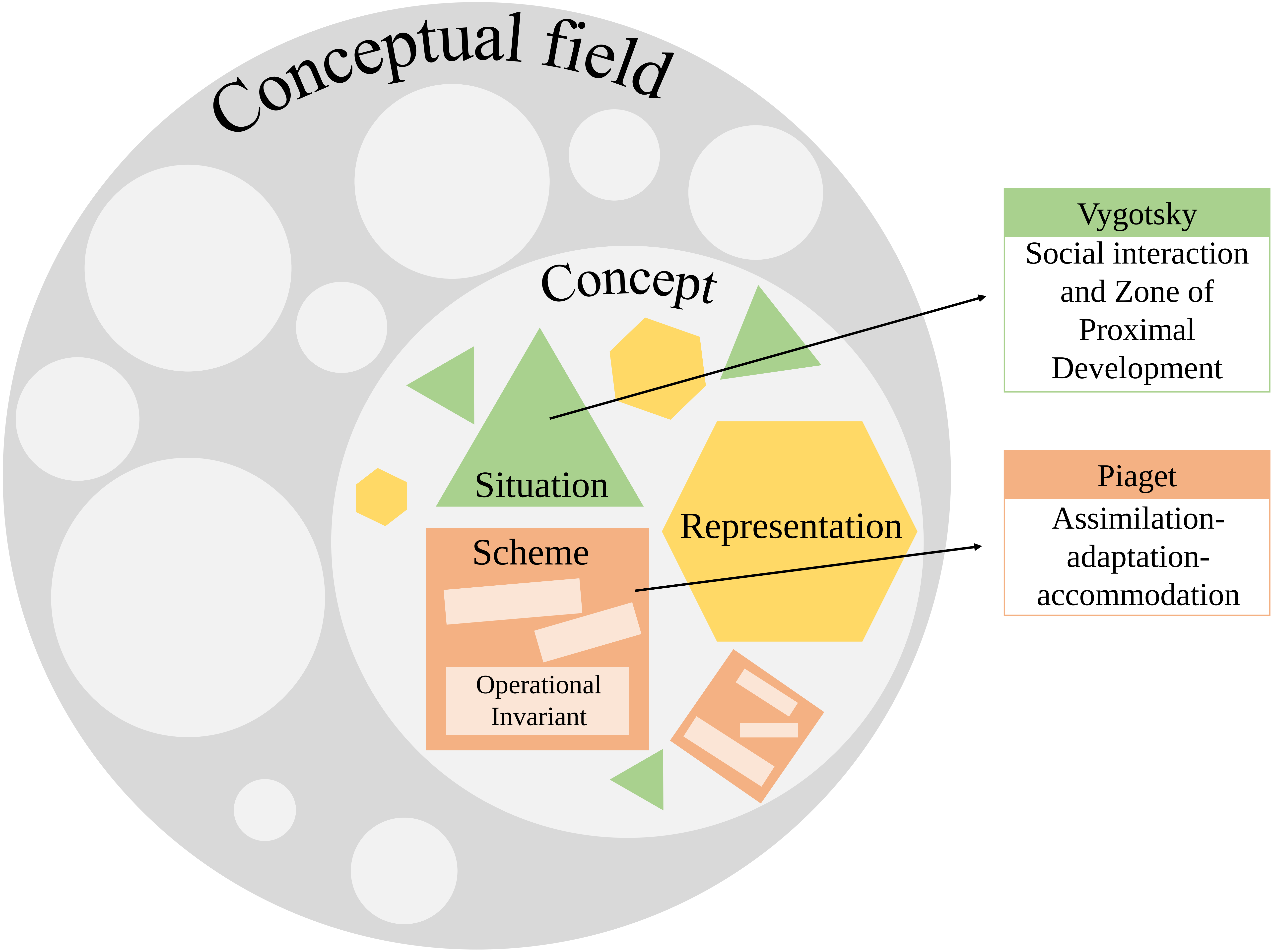
Integrated STEM education

THEORIES

- **Epistemological axis** (Laudan, 1977)
- **Psychological axis** (Vergnaud,1990)
- **Didactical axis** (Martinand, 1986)

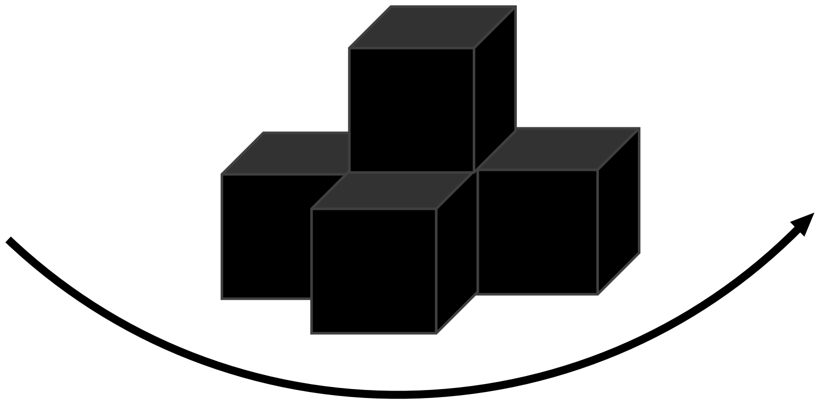
AIMS

To foster students' competence development


Conceptual field
Concept
Situation
Representation
Scheme
Operational Invariant
Vygotsky
Social interaction and Zone of Proximal Development
Piaget
Assimilation-adaptation-accommodation

TRADITIONAL CONSTRUCTION OF AN OBJECTIVE

Scheme

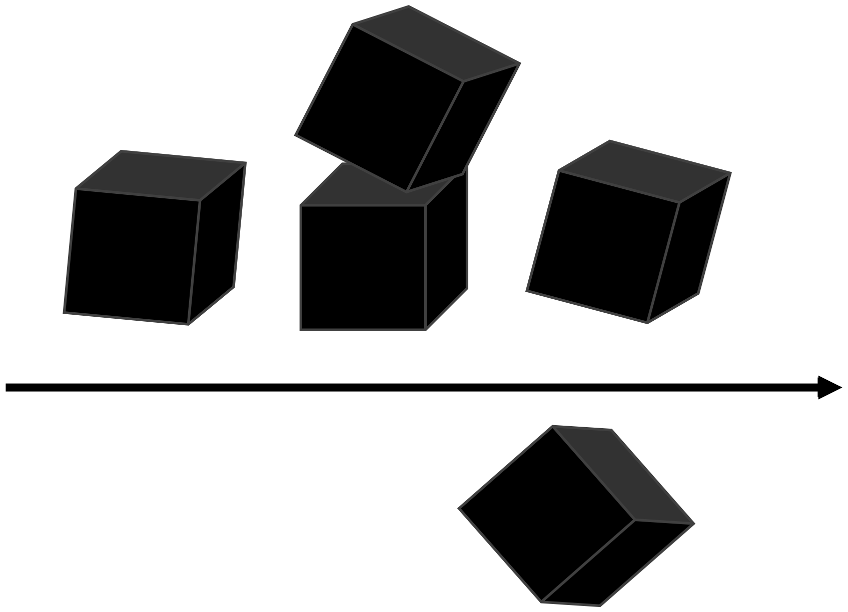


To know the basic laws that govern the transmission of an electric current

CONSTRUCTION OF OBJECTIVES FROM THE PRESENT THEORETICAL FRAMEWORK

Scheme

- The current supplied by the battery is consumed along the circuit
- An electric current is a substance —usually a fluid— that moves through wires
- The battery is the only source of charges that is injected into the wires similar to water in a pipe
- In an elementary circuit, the connection to a single battery terminal is sufficient to light the bulbs

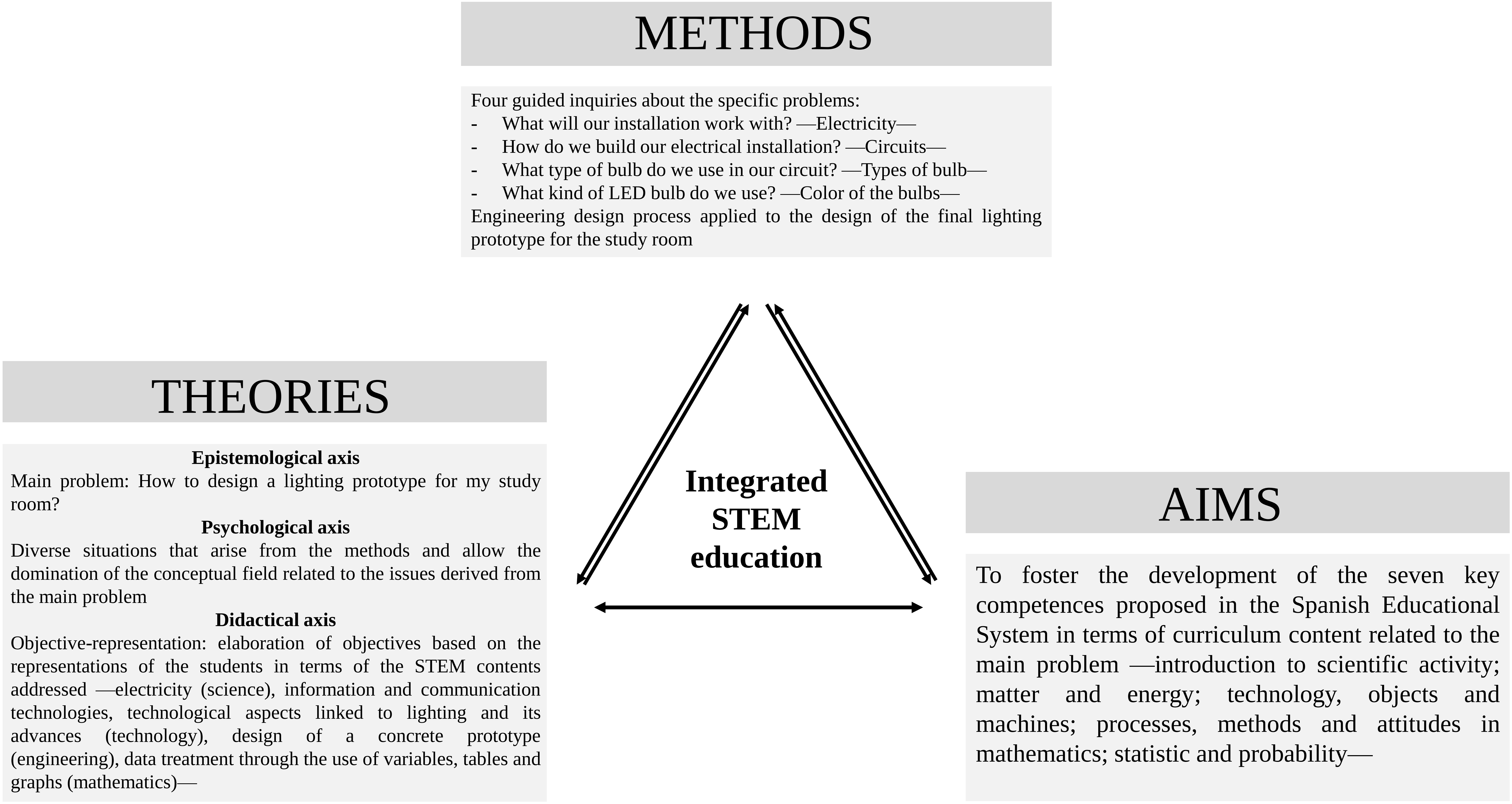


To know the chemical composition of the batteries

To understand the function of electrons in electrical currents

To understand the notion of a closed circuit

Figure 5



METHODS

Four guided inquiries about the specific problems:

- What will our installation work with? —Electricity—
- How do we build our electrical installation? —Circuits—
- What type of bulb do we use in our circuit? —Types of bulb—
- What kind of LED bulb do we use? —Color of the bulbs—

Engineering design process applied to the design of the final lighting prototype for the study room

THEORIES

Epistemological axis

Main problem: How to design a lighting prototype for my study room?

Psychological axis

Diverse situations that arise from the methods and allow the domination of the conceptual field related to the issues derived from the main problem

Didactical axis

Objective-representation: elaboration of objectives based on the representations of the students in terms of the STEM contents addressed —electricity (science), information and communication technologies, technological aspects linked to lighting and its advances (technology), design of a concrete prototype (engineering), data treatment through the use of variables, tables and graphs (mathematics)—

Integrated STEM education

AIMS

To foster the development of the seven key competences proposed in the Spanish Educational System in terms of curriculum content related to the main problem —introduction to scientific activity; matter and energy; technology, objects and machines; processes, methods and attitudes in mathematics; statistic and probability—

April 27, 2021

Sibel Erduran, PhD
Editor-in-Chief, *Science & Education*

Dear Prof. Erduran:

Thank you for giving us the opportunity to submit a revised draft with minor revisions of our Manuscript (ID SCED-D-20-00312) entitled "A theoretical framework for integrated STEM education" to *Science & Education* and for your email, dated 20 April 2021, containing the comments from the Reviewers. We appreciate the time and effort that both you as editor and Reviewers have dedicated to the review process of our manuscript. We have carefully reviewed the comments and have revised the manuscript accordingly. We have been able to incorporate changes to accommodate all of the suggestions from the Reviewers. With respect to the first reviewer's comments, we have expanded the question indicated on the introduction, added the suggested reference to disciplinary integration enriching the discourse, incorporated the excellent suggestion pointed out by the reviewer concerning the conceptualization of the students and expanded the discourse corresponding to the nature of STEM problems in the light of a recent reference. To address the second reviewer's comments, we have qualified the allusion to cooperation in relation to interdisciplinarity and the definition of didactic methodologies from the methodological level. We have also clarified the question on conceptualization that the reviewer has pertinently indicated. All the changes to the manuscript are highlighted.

We hope the revised version will now be suitable for publication and look forward to hearing from you in due course.

Sincerely,